A Factor of 2-4 Improvement in Marine Gravity and Predicted Bathymetry from CryoSat, Jason-1, and Envisat Radar Altimetry: Arctic and Coastal Regions

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LONG-TERM GOALS

- Improve our understanding of the ocean basins for scientific research and Naval operations.

OBJECTIVES

- Improve global marine gravity maps by a factor of 2 in deep ocean areas and a factor of 4 in the Arctic areas and on shallow continental margins.

- Use these improved gravity maps along with a global compilation of soundings to refine a 30-arcsecond bathymetry model (SRTM30_PLUS).

- Prepare the next generation of scientists for ocean research.

APPROACH

1. Modify waveform retracking software to improve the range precision of radar altimeter data from CryoSat, Envisat, and Jason-1.

2. Construct and assess the accuracy of new global marine gravity models based on all available radar altimeter profiles.

3. Construct global bathymetric models at 1-minute and 30-arc seconds using the new marine gravity models and all publicaly-available bathymetry sounding data.

WORK COMPLETED

We have completed the initial development of waveform retracking software for CryoSat, Envisat, and Jason-1 and have retracked all the existing data. This involved the development of a new analytic model for a SAR waveform for the open ocean similar to the Brown model waveform used for standard radar altimetry [Brown, 1977]. This research has been submitted for publication [*Garcia and Sandwell*, 2012]. Using all these data along with the Geosat and ERS-1 altimetry data we have developed a new preliminary global gravity model (V20.1 available at ftp://topex.ucsd.edu/pub/global_grav_1min).

1. REPORT DATE **2012**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **A Factor of 2-4 Improvement in Marine Gravity and Predicted Bathymetry from CryoSat, Jason-1, and Envisat Radar Altimetry: Arctic and Coastal Regions**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of California, San Diego, Scripps Institution of Oceanography 9500 Gilman Drive La Jolla, CA 92093-0225**	8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES **The original document contains color images.**

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT **SAR**	18. NUMBER OF PAGES **6**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

RESULTS

Marine gravity and bathymetry are foundational data, providing basic infrastructure for military, scientific, economic, educational, and political work. Naval operations require accurate gravity models for inertial navigation and fire control, and accurate bathymetry to assess navigational hazards in uncharted areas. In addition, coastal bathymetry is used for improving models of tides and currents.

The accuracy of the global marine gravity field depends primarily on two factors - spatial track density and altimeter range precision. Recently three new non-repeat altimeter data sets are becoming available. (1) CryoSat has been collecting data over the world's oceans for the past 2.5 years. While its main mission is to map the changing topography of the ice sheets it is also revolutionizing our understanding of marine gravity. (2) In October 2010, the Envisat radar altimeter was placed in a new partly drifting phase orbit to conserve fuel. Although the spacecraft failed in April 2012, it was able to collect 1.5 years of data along this new ground track.   (3) In May of 2012, the Jason-1 radar altimeter was maneuvered from its 10-day repeat track to a 406 day repeat track to begin its new geodetic mission phase.

The largest error source in the construction of marine gravity models from satellite altimetry is due to errors in picking the arrival time of the return radar echo. We have developed a new approach to retracking altimeter waveforms by assuming that the rise-time parameter, which represents the roughness of the ocean surface from ocean swell (SWH), varies smoothly along the satellite ground track. The results of the 20 Hz range precision for all the non-repeat altimeters are provided in the Table below.   Note the improved range precision of the newer altimeters on CryoSat, Envisat and Jason-1 with respect to the older altimeters on Geosat and ERS-1. These improvements in range precision combined with the increased track density are resulting in dramatic improvements in the accuracy of the marine gravity field. A blind test of the altimeter-derived gravity was performed by ConocoPhillips using their proprietary terrestrial gravity measurements. The rms difference between 1.4 million data points from the northern Gulf of Mexico is 1.83 mGal. The rms difference over an area of semi-permanent ice cover is 3.77 mGal.   Most of the error at lower latitude is due to errors in the E-W component because CryoSat tracks are mainly oriented N-S. Jason-1 provides better E-W coverage due to its lower orbital inclination, and if it completes a full 406-day mapping cycle, the gravity accuracy will approach the 1.5 mGal level.

Table - Altimeter Noise at 20 Hz (mm)

Altimeter	2 m SWH	6 m SWH
Geosat	57.0	105.4
ERS-1	61.8	111.8
Envisat	51.8	88.6
Jason-1	46.4	64.2
CryoSat - LRM	42.7	71.1
CryoSat - SAR	49.7	110.9

Standard deviation of retracked 20 Hz height estimates for two significant wave heights (SWH). The data are from a region of the North Atlantic with relatively high sea state. The values represent the median of thousands of estimates over a range of SWH

Over the past years, we have completed the following:

1) *Developed a new analytic model for a SAR altimeter waveform.* The shape of the return radar echo from an ocean surface is the triple convolution of the source time function, the effective area of the ocean illuminated versus time, and the ocean surface roughness function (i.e. significant wave height). When the CryoSat altimeter is operated in the SAR mode the form of the area of the ocean illuminated versus time is very different from a standard altimeter leading to a sharper return pulse (Figure 1). We have developed an analytical functional form for this return pulse shape which enables the use of standard least-squares software methods for rapidly retracking the vast amount of waveform data (~600 million waveforms/yr.)
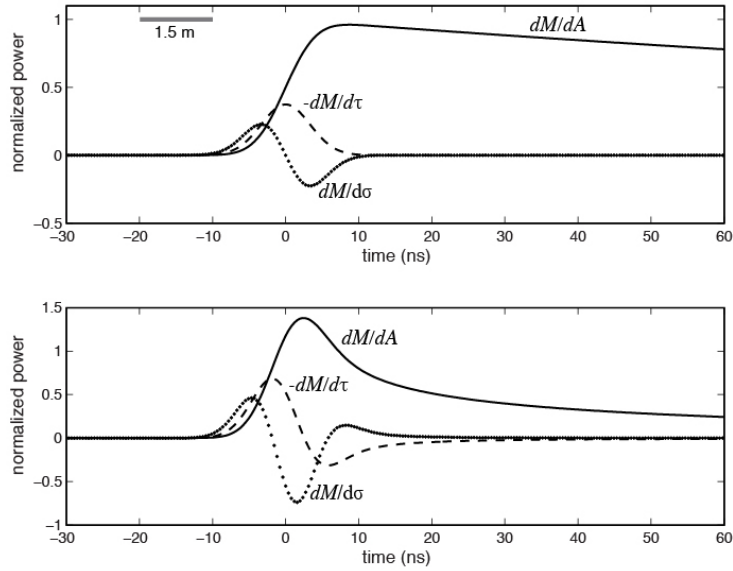

Figure 1. (upper) Brown model waveform including the exponential approximation to the trailing edge decay for a 2 m SWH. Model derivatives with respect to arrival time (dashed) and rise time (dotted) are also shown.
(lower) New SAR model waveform including the exponential approximation to the trailing edge decay for a 2 m SWH [Garcia and Sandwell, 2012]. Model derivatives are also shown.

2) *Developed and refined software for retracking all waveforms from Geosat, ERS-1, Envisat, CryoSat and Jason.* Prior to this investigation, there were no software tools for two-pass retracking of the newer altimeter data. Over the past year we have developed codes to read the raw waveform data from each satellite, reformat the data into a common waveform data structure, and retrack the data using the 2-pass retracking methods [*Sandwell and Smith,* 2005] that are optimized for gravity field recovery. Examples of along-track slope profiles and resulting gravity field around Hawaii are shown in Figure 2.

3) *Developed a new global gravity model with an accuracy of 1.71 mGal in the Gulf of Mexico.* Using these retracked altimeter profiles from all available non-repeat orbit satellite altimeters, we have constructed a new global gravity anomaly model (V20.1 available at ftp://topex.ucsd.edu/pub/global_grav_1min). The method of construction is identical to our previous

approach [*Sandwell and Smith*, 2009] so the only change is the addition of the new data. We have assessed the accuracy of the model using a shipboard gravity grid produced by Edcon Co. The rms difference between the satellite gravity and Edcon gravity is 1.71 mGal (Figure 3.). Based on these results, we expect the gravity accuracy to be better than 1.5 mGal if Jason-1 can complete one more year of its geodetic mission.
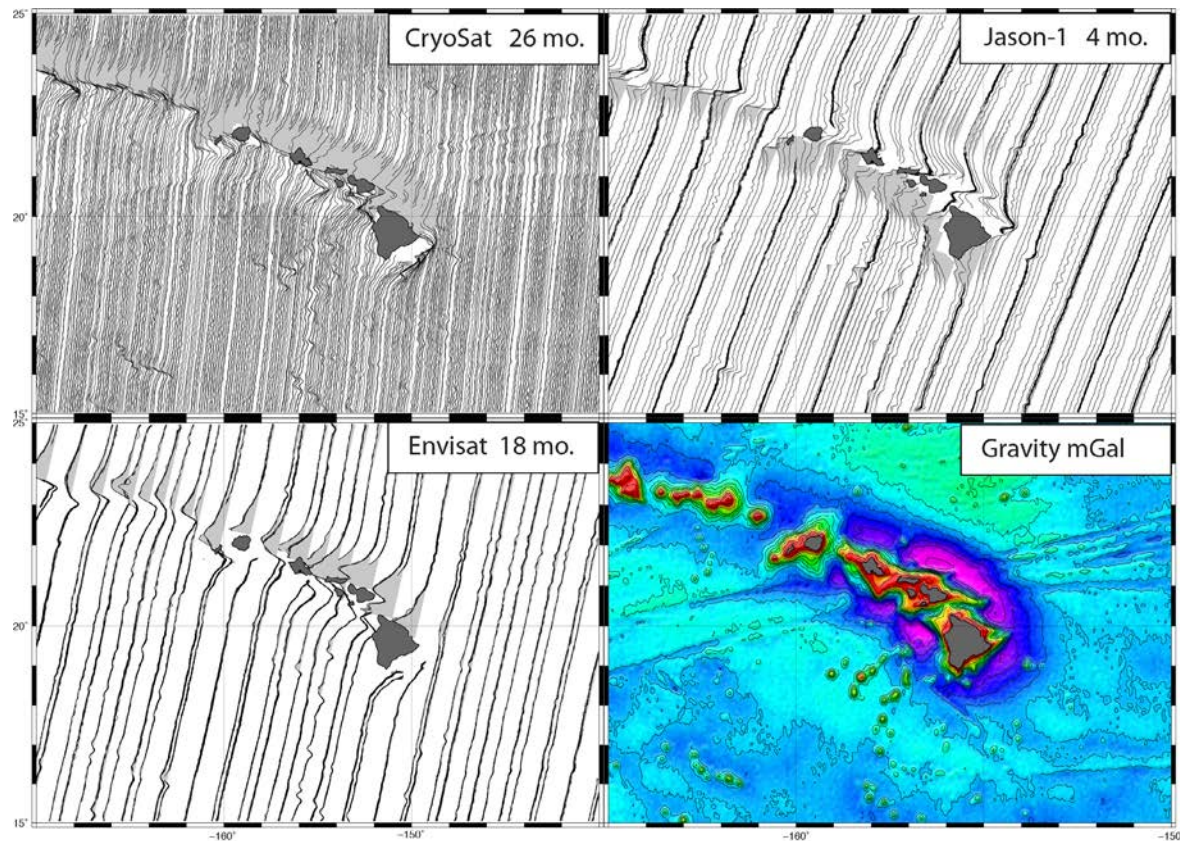
Figure 2. Along track sea surface slope from CryoSat, Envisat, and Jason-1. Track density for Jason-1 will increase by about 4 times if the satellite survives for one more year. The along-track slopes from all satellites, both ascending and descending directions, are combined using a biharmonic spline method to produce north and east sea surface slope maps and ultimately gravity anomaly (lower right).
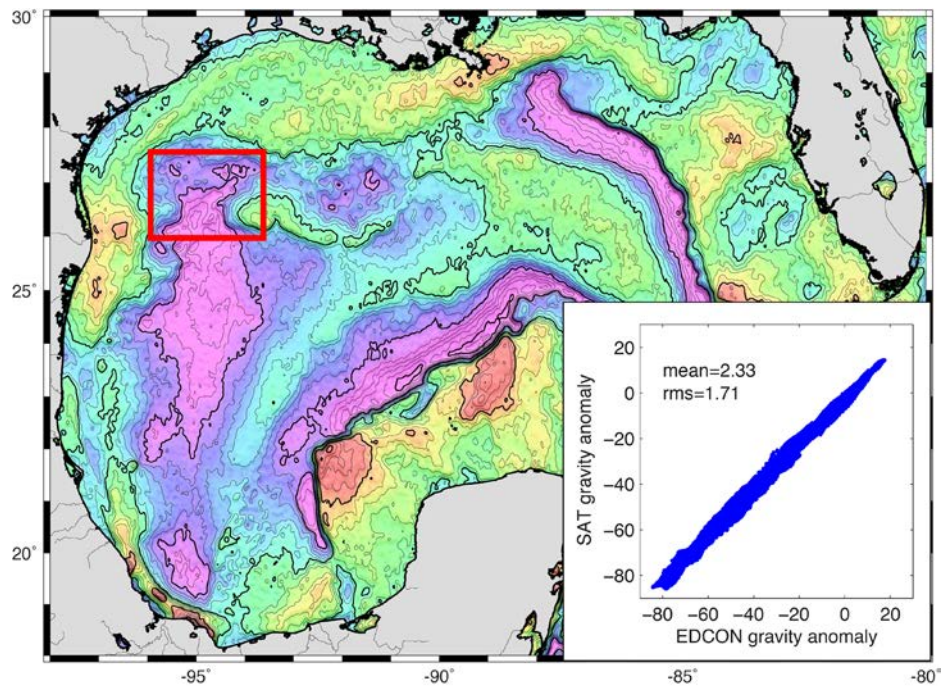
Figure 3. Gravity anomaly for the Gulf of Mexico (10 mGal contours) based on all available altimeter data. The inset shows a comparison with shipboard gravity in red box area. The rms difference is 1.71 mGal.

IMPACT/APPLICATIONS

Gravity Applications:
inertial guidance of ships, submarines, aircraft, and missiles
planning shipboard surveys
mapping seafloor spreading ridges and microplates
continental margin structure
Bathymetry Applications:
identification of navigational hazards
tsunami propagation and inundation models
tide models and tidal friction
coastal tide model improvements
ocean circulation models
tidal role in ocean mixing
understanding seafloor spreading ridges
identification of linear volcanic chains
education and outreach (i.e. geography of the ocean basins)
law of the sea

TRANSITIONS

These global gravity anomaly and bathymetry products are used throughout the Navy and defense industry in unclassified applications. For example, the National Geospatial-Intelligence Agency (Nikolaos K. Pavlis - Nikolaos.K.Pavlis@nga.mil) used our global marine gravity grid for the Earth

Gravitational Model 2008 (EGM2008; Pavlis, et al., 2008). Jim Braud (James.Braud@navy.mil) could comment on how altimetric bathymetry is used to identify "Red Dots" for survey planning as part of the Submarine Navigation Improvement Program (SNIP). Paul Sartorius (paul.k.sartorius@lmco.com) could provide details on how SRTM30_PLUS V6.0 is being used in their Google Maritime Globe for the DoD and Intel community. Paul Elmore (paul.elmore@nrlssc.navy.mil) could provide details on how our cleaned global ship soundings are being used for their "Irregular Multiresolution Database Algorithm".

RELATED PROJECTS

This research is co-funded by ConocoPhillips Co. and the National Science Foundation. All three sponsors will benefit from improved marine gravity and bathymetry.

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PUBLICATIONS

Garcia, E. S., and D. T. Sandwell, Retracking CryoSat-2, Envisat, and Jason-1 Radar Altimetry Waveforms for Optimal Gravity Field Recovery, *submitted to Geophysical J. Int.,* October, 2012.